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UTILITY PATENT APPLICATION TRANSMITTAL

(Apply for new nonprovisional applications under 37 C.F.R. 1.53(b))

Attorney Docket No.	18180.0016	Total Pages	34
First Named Inventor or Application Identifier			
Donald Specht			
Express Mail Label No.			

APPLICATION ELEMENTS <i>See MPEP chapter 600 concerning utility patent application contents</i>	Assistant Commissioner for Patents Box Applications Washington, DC 20231
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1. Fee Transmittal Form
(Submit an original, and a duplicate for fee processing)
2. Specification [Total Pages [27]]
(preferred arrangement set forth below)
 - Descriptive title of the invention
 - Cross References to Related Applications
 - Statement Regarding Fed sponsored R & D
 - Reference to Microfiche Appendix
 - Background of the Invention
 - Brief Summary of the invention
 - Brief Description of the Drawings *(if filed)*
 - Detailed Description
 - Claim(s)
 - Abstract of the Disclosure
3. Drawing(s) *(35 USC 113)* [Total Pages [7]]
4. Oath or Declaration [Total Pages [1]]
 a. Newly executed (original or copy)
 b. Copy from a prior application (37 CFR 1.63(d))
(for continuation/divisional with Box 17 completed)
 DELETION OF INVENTOR(S)
 Signed statement attached deleting inventor(s) named in the prior application, see 37 CFR 1.63(d)(2) and 1.33(b)
5. Incorporation By Reference *(useable if Box 4b is checked)* The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied under Box 4b, is considered as being part of the disclosure of the accompanying application and is hereby incorporated by reference therein.

6. Microfiche Computer Program *(Appendix)*
 7. Nucleotide and/or Amino Acid Sequence Submission *(if applicable, all necessary)*
 a. Computer Readable Copy
 b. Paper Copy *(identical to computer copy)*
 c. Statement verifying identity of above copies

ACCOMPANYING APPLICATION PARTS

8. Assignment Papers (cover sheet & document(s))
 9. 37 CFR 3.73(b) Statement Power of Attorney
 10. English Translation Document *(if applicable)* Copies of IDS
 11. Information Disclosure Statement (IDS)/PTO-1449 Citations
 12. Preliminary Amendment
 13. Return Receipt Postcard (MPEP 503)
(Should be specifically itemized)
 14. Small Entity Statement filed in prior application(s) Status still proper and desired
 15. Certified Copy of Priority Document(s) *(if foreign priority is claimed)*
 16. Other:

17. If a **CONTINUING APPLICATION**, check appropriate box and supply the requisite information:
 Continuation Divisional Continuation-in-part (CIP) of prior application No. _____

18. CORRESPONDENCE ADDRESS

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FEE TRANSMITTAL

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METHOD OF PAYMENT (check one)		FEE CALCULATION (continued)																																																																																																																																																																					
1. <input checked="" type="checkbox"/> The Commissioner is hereby authorized to charge indicated fee and credit any over payments to: <input checked="" type="checkbox"/> Deposit Account Number 19-5127 (Referencing order no. 18180 0016) Deposit Account Name Swidler Berlin Shreffl Friedmann, LLP <input checked="" type="checkbox"/> Charge Any Additional Fee Required Under 37 CFR 1.16 and 1.17 <input type="checkbox"/> Charge the Fee Set in 37 CFR 1.18 at the Mailing of the Notice of Allowance, 37 CFR 1.311(b)		ADDITIONAL FEES <table border="1"> <thead> <tr> <th>Large Fee Code</th> <th>Entity Fee (\$)</th> <th>Small Entity Fee Code</th> <th>Entity Fee (\$)</th> <th>Fee Description</th> <th>Fee Paid</th> </tr> </thead> <tbody> <tr> <td>105</td> <td>130</td> <td>205</td> <td>65</td> <td>Surcharge - late filing fee or oath</td> <td></td> </tr> <tr> <td>127</td> <td>50</td> <td>227</td> <td>25</td> <td>Surcharge - late provisional filing fee or cover sheet</td> <td></td> </tr> <tr> <td>139</td> <td>130</td> <td>239</td> <td>65</td> <td>Non-English specification</td> <td></td> </tr> <tr> <td>147</td> <td>2,520</td> <td>147</td> <td>2,520</td> <td>For filing a request for reexamination</td> <td></td> </tr> <tr> <td>112</td> <td>920'</td> <td>112</td> <td>920'</td> <td>Requesting publication of SIR prior to Examiner action</td> <td></td> </tr> <tr> <td>113</td> <td>1,790'</td> <td>113</td> <td>1,790'</td> <td>Requesting publication of SIR after Examiner action</td> <td></td> </tr> <tr> <td>115</td> <td>110</td> <td>215</td> <td>55</td> <td>Extension for response within first month</td> <td></td> </tr> <tr> <td>116</td> <td>400</td> <td>216</td> <td>200</td> <td>Extension for response within second month</td> <td></td> </tr> <tr> <td>117</td> <td>950</td> <td>217</td> <td>475</td> <td>Extension for response within third month</td> <td></td> </tr> <tr> <td>118</td> <td>1,510</td> <td>218</td> <td>755</td> <td>Extension for response within the fourth month</td> <td></td> </tr> <tr> <td>128</td> <td>2,060</td> <td>228</td> <td>1,030</td> <td>Extension for response within the fifth month</td> <td></td> </tr> <tr> <td>129</td> <td>310</td> <td>219</td> <td>155</td> <td>Notice of Appeal</td> <td></td> </tr> <tr> <td>120</td> <td>310</td> <td>220</td> <td>155</td> <td>Filing a brief in support of an appeal</td> <td></td> </tr> <tr> <td>121</td> <td>270</td> <td>221</td> <td>135</td> <td>Request for oral hearing</td> <td></td> </tr> <tr> <td>140</td> <td>110</td> <td>240</td> <td>55</td> <td>Petition to revive unavoidably abandoned application</td> <td></td> </tr> <tr> <td>141</td> <td>1,320</td> <td>241</td> <td>660</td> <td>Petition to revive unintentionally abandoned application</td> <td></td> </tr> <tr> <td>142</td> <td>1,320</td> <td>242</td> <td>660</td> <td>Utility issue fee (or reissue)</td> <td></td> </tr> <tr> <td>143</td> <td>450</td> <td>243</td> <td>225</td> <td>Design issue fee</td> <td></td> </tr> <tr> <td>144</td> <td>670</td> <td>244</td> <td>335</td> <td>Plant issue fee</td> <td></td> </tr> <tr> <td>122</td> <td>130</td> <td>122</td> <td>130</td> <td>Petitions to the Commissioner</td> <td></td> </tr> <tr> <td>123</td> <td>50</td> <td>123</td> <td>50</td> <td>Petitions related to provisional applications</td> <td></td> </tr> <tr> <td>126</td> <td>240</td> <td>126</td> <td>240</td> <td>Submission of Information Disclosure Statement</td> <td></td> </tr> <tr> <td>581</td> <td>40</td> <td>581</td> <td>40</td> <td>Recording each patent assignment per property (times number of properties)</td> <td></td> </tr> <tr> <td>146</td> <td>790</td> <td>246</td> <td>395</td> <td>Filing a submission after final rejection (37 CFR 1.129(a))</td> <td></td> </tr> <tr> <td>149</td> <td>790</td> <td>249</td> <td>790</td> <td>For each additional invention to be examined (37 CFR 1.129(b))</td> <td></td> </tr> <tr> <td colspan="4">Other fee (specify) _____</td> <td>SUBTOTAL (3)</td> <td>710.00</td> </tr> </tbody> </table>				Large Fee Code	Entity Fee (\$)	Small Entity Fee Code	Entity Fee (\$)	Fee Description	Fee Paid	105	130	205	65	Surcharge - late filing fee or oath		127	50	227	25	Surcharge - late provisional filing fee or cover sheet		139	130	239	65	Non-English specification		147	2,520	147	2,520	For filing a request for reexamination		112	920'	112	920'	Requesting publication of SIR prior to Examiner action		113	1,790'	113	1,790'	Requesting publication of SIR after Examiner action		115	110	215	55	Extension for response within first month		116	400	216	200	Extension for response within second month		117	950	217	475	Extension for response within third month		118	1,510	218	755	Extension for response within the fourth month		128	2,060	228	1,030	Extension for response within the fifth month		129	310	219	155	Notice of Appeal		120	310	220	155	Filing a brief in support of an appeal		121	270	221	135	Request for oral hearing		140	110	240	55	Petition to revive unavoidably abandoned application		141	1,320	241	660	Petition to revive unintentionally abandoned application		142	1,320	242	660	Utility issue fee (or reissue)		143	450	243	225	Design issue fee		144	670	244	335	Plant issue fee		122	130	122	130	Petitions to the Commissioner		123	50	123	50	Petitions related to provisional applications		126	240	126	240	Submission of Information Disclosure Statement		581	40	581	40	Recording each patent assignment per property (times number of properties)		146	790	246	395	Filing a submission after final rejection (37 CFR 1.129(a))		149	790	249	790	For each additional invention to be examined (37 CFR 1.129(b))		Other fee (specify) _____				SUBTOTAL (3)	710.00
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FEE TRANSMITTAL**PAGE 2**

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First Named Inventor	Donald F. Specht
Group Art Unit	
Examiner Name	

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Typed or Printed Name	Robert C. Bertin	Registration Number	41,488	
Signature		Date	10/24/00	Deposit Account User ID
				19-5127

USPTO USE ONLY

**APPARATUS AND METHOD FOR EFFICIENTLY INCREASING THE
SPATIAL RESOLUTION OF IMAGES**

Inventors: Donald F. Specht
5 Peter Stanek
 Robert Marc Drake

FIELD OF THE INVENTION:

The present invention relates generally to image processing and more
10 particularly to techniques for enhancing the spatial sharpness or resolution of an
image using a higher resolution, substantially co-registered image.

BACKGROUND OF THE INVENTION:

Image processing refers to any and all activities that acquire, manipulate,
15 store and display images. Many specific useful applications arise in, for example,
photography, medical imaging and satellite imaging.

Images are typically acquired with a camera or scanner that exposes
sensors or film that register a single spectral band or multiple spectral bands of
incident radiation from a scene to be imaged. Monochrome images are examples
20 of images acquired using a single spectral band. Color images are examples of
images acquired using several spectral bands that represent blue, green, and red
signals. In general, multi-spectral images contain more useful information than
single spectral band images. However, sensors or film used in cameras or
scanners that acquire multi-spectral images are more complex and expensive than
25 sensors or film used to acquire single spectral band images. The cost of cameras
and sensors to acquire high quality multi-spectral images at high resolutions may
be extremely expensive.

The performance of an image processing system can be measures in many ways. One measure is “resolution,” or the ability to distinguish different scene objects or materials in the processed image. “High resolution” means the processed image shows different objects that are closely spaced in the scene.

5 Such “high resolution” is more properly termed “high spatial resolution.” The term “high spectral resolution” refers to the system’s ability to distinguish some elements that are closely related in electromagnetic wavelength.

Because of the high cost of acquiring high spatial resolution, multi-spectral images directly, it would be desirable to acquire multi-spectral images
10 using lower resolution cameras and to increase the resolution of the acquired images in a less expensive way.

One conventional technique for increasing the spatial resolution of a low resolution image is described in a paper entitled “Adaptive Image Sharpening using Multiresolution Representations” by A. Evan Iverson and James R. Lersch,
15 SPIE Volume 2231, 5 April 1994. This technique uses a high-resolution image acquired from a single band sensor to enhance the resolution of a co-registered, low resolution, multi-spectral band image. Specifically, the technique disclosed therein relies upon computationally demanding and complex steps of creating Gaussian and Laplacian pyramids to find relationships between the high-
20 resolution and low resolution images that are then used to map pixels from the high resolution image to the low resolution image, creating a synthetic image with improved spatial resolution.

It is desirable to provide a method of increasing the spatial resolution of a low-resolution, multi-spectral image that is fast and less computationally demanding than the Iverson and Lersch technique. It is further desirable to provide a method of increasing the spatial resolution of a low-resolution, multi-spectral image using at least one high resolution image in a way that closely approximates the spectral content of interest from the low resolution image.

5

Another prior art technique is the Projective Pan Sharpening Algorithm (published by John Lindgren and Steven Kilston as paper #2818-26, SPIE '96, Denver, Colorado). This technique assumes nearly complete spectral overlap between a panchromatic band and that multi-spectral bands it is used to sharpen. It also assumes a linear relationship between intensities in the pan and multi-spectral bands. The present technique requires neither of these assumptions.

10

The Pradines algorithm and the Price algorithm, referenced in the Lindgren and Kilston paper, each also are based on the linearity assumption, whereas the present technique can have different relationships for different spectral signatures.

15

SUMMARY OF THE INVENTION:

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According to one embodiment of the present invention, a method has been found that effectively and efficiently increases the apparent spatial resolution of a source image based on an auxiliary, co-registered image of a higher spatial resolution. In what follows, an image is a collection of pixels. A pixel is the smallest unit of spatial subdivision. Some elements smaller than one pixel cannot

be distinguished. A pixel represents the total information collected by the image system sources. Each of the source and auxiliary images includes a plurality of pixels with corresponding spectral intensities. The method follows five steps: reducing, identifying, deriving, subdividing and modifying procedures.

5 In the reducing step, the spatial resolution of the auxiliary image is reduced to a common spatial resolution with that of the source image. Then in the identifying step, corresponding groups of pixels at the common resolution in the source and auxiliary images are identified. In the deriving step, a map is derived associating differences in the spectral intensities of adjacent pixels in the auxiliary
10 image with differences in the spectral intensities of corresponding adjacent pixels in the source image.

In the subdividing step, each source pixel is subdivided according to the geometry of the associated auxiliary pixels. Then in the modifying step, the spectral intensity for each subdivided source pixel is computed using the map.
15 The result is an apparent increased resolution of the source image.

The method does not use computationally demanding Gaussian or Laplacian pyramids as described in the article by Iverson and Lersch. For this reason, methods according to the present invention are faster than the Iverson and Lersch techniques at image sharpening.

20

BRIEF DESCRIPTION OF THE FIGURES:

These and other objects, features and advantages of the invention will be more fully appreciated with reference to the detailed description and appended drawing figures.

Fig. 1 depicts an image processor coupled to peripheral devices.

5 Fig. 2 depicts an internal view of a camera that provides source and auxiliary images to the image processor according to an embodiment of the present invention.

Fig. 3A-3C depict a method of increasing the spatial resolution of the source image according to an embodiment of the present invention.

10 Fig. 4 depicts resampling an auxiliary image to common resolution with the source image.

Fig. 5 depicts forming an average pixel for each group of pixels according to one embodiment of the present invention.

15 Fig. 6 depicts forming image difference groups according to one embodiment of the present invention.

Fig. 7 depicts corresponding pixels between groups of a source and auxiliary image according to the present invention.

Fig. 8 depicts subdividing source pixels according to one embodiment of the present invention.

20 Fig. 9 depicts mapping pixel intensities from the auxiliary image to the subdivided pixels of the source image according to one embodiment of the present invention.

DETAILED DESCRIPTION:

Fig. 1 depicts an image processor 10 in which the invention may illustratively find application. The image processor 10 is coupled to a camera or scanner 12, a database 14, a network 16, a printer 18 and a monitor 20.

5 Typically the camera 12 is a digital system that is equipped with N filters for determining intensities at each of N frequencies or spectral bands of interest in a field of view. The camera 12 outputs N-dimensional pixel data. Each pixel specifies a spatial location within an image of the field of view and N spectral intensities associated with the location. As an alternative to a digital camera, film
10 camera may be used to capture photographic images of the field of view. In this scenario, the camera 12 may be a scanner which scans N photographic negatives or prints and outputs N-dimensional pixel data of the scanned image. The camera 12 may be hand-held or mounted in a remote location, such as an airplane or a satellite.

15 Internally, the camera 12 may include either multiple cameras or multiple sensors that are co-registered to capture impinging radiation from the field of view. For example, referring to Fig. 2, the camera 12 may include a high-resolution camera or sensor 30 and a low resolution, multi-spectral camera or sensor 32.

20 The high-resolution camera or sensor 30 may capture a single or multiple spectral bands. In one embodiment, the high resolution sensor 30 is a high-resolution panchromatic sensor, which outputs a single intensity that represents an aggregation of a wide range of spectral bands. Alternatively, a sensor which

captures and outputs either a single or multiple narrow spectral band(s) may be used. Typically, the high-resolution camera or sensor 30 will be less expensive to implement than a camera or sensor configured to acquire all of the spectral bands of interest at the same, high resolution. The high resolution camera or sensor 30 outputs an N dimensional auxiliary image 34 of the field of view to the image processor 10. For the auxiliary image 34, N is typically 1 and typically represents the panchromatic band. However, N may be greater than one and the spectral bands may be any convenient band or bands within or outside of the visible spectrum. Only one auxiliary band must have high resolution. The other auxiliary image bands can have any resolution equal to or better than that of the source image.

The low resolution camera or sensor 32 may be configured to capture multiple spectral bands of interest of a field of view that is co-registered with the high-resolution camera 30. The low resolution camera 32 outputs an N dimensional, low resolution source image 36 of the field of view to the image processor 10. From a group of co-registered images of various resolutions, one is chosen as the "source image", i.e. the one to be enhanced, one is chosen as the primary auxiliary image and must have higher spatial resolution than the source. Any or all of the images can be included as auxiliary images and will serve to improve a spectral discrimination for each pixel of the source. Preferably, the spatial resolution of the auxiliary image is an integer multiple greater than the source image in any and/or all dimensions.

The image processor 10 may receive imaging data in real time from the camera 12 and process the imaging data in real time for output to the monitor 20 or printer 18. Alternatively, the image processor 10 may output processed images to the database 14 or the network 16. The network 16 may illustratively include a local area or wide area network, a telecommunications network or the network of interconnected computers and computer networks known as the Internet. The image processor 10 may also receive imaging data, representing the source image 36, auxiliary image, 34, and, possibly additional auxiliary images 35, from the database 14 or the network 16 instead of the camera 12. The image processor 5 then processes the imaging data and sends the resulting processed image to any of the output devices 14-20.

Fig. 3 depicts a method of increasing the spatial resolution of the source image 36 using the auxiliary image 34 according to an embodiment of the present invention. The method is not complex and does not use the computationally demanding Gaussian or Laplacian pyramids as described in the article by Iverson and Lersch. Because the computations are simple and relatively few, a method according to the present invention is much faster than the Iverson and Lersch techniques at image sharpening.

First, the method will be described using a single auxiliary image. In step 100, the image processor 10 acquires the source and auxiliary images 36 and 34, respectively. The acquired source image 36 has a lower spatial resolution than the acquired auxiliary image 34. For this reason, the source image 36 has fewer, larger pixels than the auxiliary image 34 as shown in Fig. 4. Additional auxiliary

images 3-5 may also be acquired but are not used in this illustration. The image processor 10 may acquire the images 34 and 36 from the camera 12, the database 14 or the network 16.

In step 102, the image processor 10 re-samples all of the high resolution pixels 52 of the auxiliary image 34 to have the same spatial resolution of the source image 36. This step is shown graphically in Fig. 4. In the simplest case, the auxiliary image 34 has a resolution that is an integer multiple of the source image 36 in any single or all dimensions. In this case, the image processor 10 defines clusters 50 within the high resolution pixels 52 based on the integer multiple of each linear dimension. For example, if the auxiliary image has twice as many pixels in each linear dimension, then each group 50 will include a 2x2 array of high resolution pixels 52. Similarly, if the auxiliary image has three times as many pixels in each linear dimension, than each group 50 will include a 3x3 array of high resolution pixels 52. For each group 50, the image processor 10 forms at least one average coarse pixel 54. The average coarse pixel(s) for each group 50 is equal to the average of spectral intensities for the high resolution pixels 52 in each group 50. More sophisticated and accurate sub-sampling techniques known in the literature (see, for example, Digital Image Processing, W.K. Pratt, John Wiley & Sons, New York, 1978) could be used instead of simple averaging.

The set of coarse pixels 54 and 55 is then used as the resampled pixel values that comprise the re-sampled auxiliary image. The coarse pixels 54 in the

source image 36 and the coarse pixels 55 in the auxiliary image 34 have the same spatial resolution after step 102. This is illustrated in the following examples.

Example 1

Source Image: 200 x 200 pixels

5 Auxiliary Image: 400 x 400 pixels from panchromatic sensor

Multiple: (2x in each linear dimension)

Common Resolution: 200x200

To resample the 400x400 pixel auxiliary image, define groups 50 of pixels in the auxiliary image as 2x2 groups of high-resolution pixels 52. Take the average pixel intensity value of each group 50 and define a new, coarse pixel 55 representing each group in the re-sampled 200x200 pixel auxiliary image. There is no need to resample the source image because the re-sampled auxiliary image has been converted to the same spatial resolution as the source image.

15 Example 2

Source Image: 300x300 pixels

Auxiliary Image: 800x800 pixels from panchromatic sensor

20 Multiple: (2.66x in each linear dimension)

Common Resolution: 300x300 pixels

Because the spatial resolution of the auxiliary image is not an integer multiple of the spatial resolution of the source image, the auxiliary image is resampled twice. First, the auxiliary image 34 is resampled to an intermediate spatial resolution of 600x600 pixels. This resampling is done by converting each

1.33 pixels in the 800x800 pixel auxiliary image 34 to 1 pixel using pixel interpolation. Subsequently, the intermediate auxiliary image 34 is resampled a second time by grouping high resolution pixels 52 in the auxiliary image 34 into 2x2 groups 50. The average pixel intensity value of each 2x2 group 50 defines a new, coarse pixel 55 representing each group in the 300x300 pixel resampled auxiliary image 38. There is no need to resample the source image 36 because the resampled auxiliary image 38 is at the same spatial resolution as the source image 36.

In step 104, the image processor 10 identifies groups 60 of coarse pixels 54 within the source image 36 and groups 61 of coarse pixels 55 within the resampled auxiliary image 38. An average coarse pixel 62 is then determined for each group 60 of coarse pixels 54 within the source image 36 and the auxiliary image 34. This is shown in Fig. 5.

When the pixels in the auxiliary image have only one spectral intensity value corresponding to a single spectral band, then averaging is performed one time to determine one average coarse pixel for each group 60. When either the source image 36 or auxiliary image 34 has N spectral intensities corresponding to N spectral bands (as is most often the case with the source image 36), an average coarse pixel 62 is determined for each group of coarse pixels 60 at each spectral band. For example, in the case of a source image represented using red, green, and blue bands, an average coarse pixel for each of the red, green and blue intensities may be determined for each group 60 and 61.

In step 106, the image processor 10 subtracts the average coarse pixel 62 for each group 60 from each coarse pixel 54 in the same group, and also subtracts the average coarse pixel 63 for each group 61 from each coarse pixel 55 in the same group. The result is a new group called a pixel difference group 70 and 71.

5 For example, given pixel intensities of 1, 2, 3 and 4 within a 2x2 group 60, the average coarse pixel 62 has an intensity of 2.5. Therefore, the pixel difference group 70 corresponding to the 2x2 group 60 includes the following pixel difference values: -1.5, -0.5, 0.5 and 1.5. Step 106 is performed on all groups 60 and 61 in the source image 36 and the resampled auxiliary image 38, respectively.

10 In step 108, the image processor 10 computes a gain between corresponding pixels in the pixel difference groups 70 of the source image 36 and groups 71 of the auxiliary image 38. This is graphically illustrated in Fig. 7 with lines 76 indicating corresponding and associated pixel groups. When the auxiliary image includes multiple spectral bands, the image processor 10 computes the gain value as a function of the spectral signature represented by the plurality of pixel values represented by the image planes. The source pixel can be used as one component of the spectrum. Step 108 is repeated for every pixel difference group in the source image 36 and resampled auxiliary image 38.

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The basic assumption of the technique is that the ratio of small changes in the higher resolution auxiliary image to changes in the source image calculated at lower resolution, will be characteristic for the imaged material represented in a pixel. The assumption is that this ratio will still be correct for high spatial frequencies beyond the cutoff of the sensor for the source pixels. Thus it is

desired to compute a mapping of the characteristics of the reflecting material to
the ratio of small changes in the auxiliary image to small changes in the source
image. It is expected that the ratio will be different for different materials. If
many auxiliary bands are present, the material can be identified by its spectral
signature. If only one auxiliary band is present, then the material must be
identified (less reliably) by only the two large pixels available.

In step 110, imaging data for the source image 36 and resampled auxiliary
image 38 acquired and calculated in steps 100-108 are stored in the database 14
for application to a mapping function. The mapping function determines
relationships between co-located pixels from the source image 36 and the
resampled auxiliary image 38. The imaging data applied to the mapping function
may be any of the following: intensities of pixels 54 of the source image 36 or
pixels 53, resampled auxiliary image 38, gain values determined in step 108;
difference values determined in step 106, or average pixel intensities determined
in step 104.

The imaging data in step 110 is generally comprised of an array of pixels,
where each pixel represents a position on a source image 34 or an auxiliary image
36 and a spectral profile of the position. The spectral profile is represented by an
N-dimensional vector having N spectral intensities. For many applications, N is 3
and each of the three spectral intensities represents a respective intensity in the
visible light portion of the spectrum, such as red, green or blue color.
Combinations of varying red, green and blue intensities may be perceived as a
large range of colors in the visible spectrum. For other applications, N may be

greater or less than 3 and the respective spectral intensities may be measured within and outside of the visible portion of the electromagnetic spectrum. For example, in the case of the TMS and MAMS imaging sensors, N is 11 and includes frequencies in the infra-red portion of the electromagnetic spectrum. In
5 the case of AVIRIS imaging data, N is 224 and includes a wide range of frequencies. AVIRIS and similar sensor data may include sufficient spectral information on the materials represented in the image to allow classification of the materials.

The auxiliary image 34, like the source image 36, may also have N
10 dimensional pixel data where N may be 1, 3, 11, 224 or any other convenient number. However, at least one band of the auxiliary image 34 must have higher resolution than the source image to permit spectral sharpening according to the present invention.

For any given co-located pixel in the source image 36 and the auxiliary image 34, an intensity vector describes the spectral content of the material represented by the pixel. The intensity vector, therefore, includes spectral intensities for the source image and the auxiliary image and has a dimensionality that is the sum of the number of spectral bands in the source and auxiliary images.
15 The intensity vector may permit identification of the material represented by the pixel and at a minimum identifies materials with similar imaged characteristics.
The average source and auxiliary image pixels calculated in step 104 may be used
20 for the intensity vector.

Also, for any given co-located pixel in the source image 36 and the auxiliary image 34, a gain vector describes the relationship between differential changes in pixel intensities of the auxiliary image to differential changes in pixel intensities of the source image. The gain which is determined based on steps 106 and 108 as described, is typically a ratio of differential source pixel intensity to differential auxiliary image pixel intensity. For each pixel, one ratio is typically formed for each spectral band in the source image as a ratio to each spectral band in the auxiliary image 24 that has a higher spatial resolution than the source image. Each gain is generally only valid for pixels that have imaged vectors that are close to the imaged vector of the underlying pixels in the source image 36 and auxiliary image 34 for which the gain was calculated.

In step 112, a mapping function is derived and stored in the database 14. In general, if the intensity vector has many components representing multispectral data, the mapping function cannot be a simple table lookup because the table could be impractically large with sparse data. What is desired is a table lookup which interpolates measured gains in the vicinity of the intensity vector. The mapping function is amenable to several neural network implementations, including: a general regression neural network (GRNN); a probabilistic neural network (PNN); Multi-Layer Perceptron (MLP) or K Nearest Neighbors (KNN). GRNN or MLP or KNN estimate the differential gains directly. PNN classifies patterns into one of several categories. The category information, in turn, is used to indicate the amount of change necessary for a given small pixel relative to a corresponding large pixel. Alternatively, the category information could indicate

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the local gain relating the differential change in the auxiliary image to that for the source image. The neural networks may be implemented in hardware, software or a hybrid of hardware and software. Vector quantization, fuzzy logic, genetic algorithms, applied statistics and other neural networks may also be used for the mapping function. Further discussion of certain neural network and other embodiments follows.

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After deriving the mapping in step 112, the higher-resolution source image is created as illustrated in steps 114-120. To facilitate explanation of the method, a “large pixel” is defined as the smallest pixel of the original source image and as a pixel of the same size in the principal auxiliary image, which typically must be calculated by averaging even smaller pixels present in the principal auxiliary image. Pixels 54 of the re-sampled auxiliary image 38 are large pixels. A “small pixel” is defined as the desired pixel size for the enhanced source image. In the example discussion, there are four small pixels cover the same area as one large pixel, but different mappings, or numbers of small pixels such as five, nine, sixteen or any other convenient number, may be used. The only requirements are that the small pixels of the principal auxiliary image match the small pixels of the enhanced source and that an integral number of small pixels are covered by one large pixel. In step 114, each large pixel of the source image 34 is subdivided into small pixels (typically a 2x2 array).

In step 116, for each small pixel of the corresponding large pixel of the principal auxiliary image, compute the difference between it and the large pixel intensity (which is the average of all of the small pixels it covers). Then, in step

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118, for each small pixel, the processor 10 retrieves from the mapping in the database a stored intensity vector to which the intensity vector of the corresponding large pixel in the source and the auxiliary image is the closest. In step 120, the processor 10 computes new small pixel intensities for each color or spectral band of the enhanced source image as the intensity of the large source pixel + (the associated gain) times (the difference between the small pixel and large pixel of the principal auxiliary image).

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After all of the large pixels 54 of the source image 36 have been mapped to new small pixels 82 based on the pixel differences of the auxiliary image and the gain values, the new pixels 82 are output in step 120 as the processed image. The processed, source image has a higher resolution than the original source image.

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To illustrate a specific embodiment of the method of the present invention, the following conditions are assumed. The imaging data applied to the mapping function in step 110 are the intensities of the average pixels determined in step 104 for the source image 34 and the auxiliary image 36 and the gains between pairs 76 of corresponding pixels of the source and resampled auxiliary image difference clusters 70. The pixels of the source image are three dimensional, having red, green and blue intensities. The pixels of the auxiliary and resampled auxiliary image are one dimensional, having a single panchromatic intensity.

A. Vector Quantization

Step 112 may be performed using a clustering technique, such as vector quantization. Suppose for example that a three-color image and a co-registered panchromatic image are available. Each of the three color planes are to be enhanced, one at a time. One is chosen as the source, the panchromatic image is the principal auxiliary image, and all three color planes are used as additional auxiliary images. According to this embodiment, the image processor 10 assembles a codebook relating gain to imaged object as identified by spectral signature. First a conditional gain must be calculated for each average pixel determined in step 104 for each color in the source image 34. To accomplish this, four conditional gains are first calculated in steps 106 and 108 based on the 2x2 matrix of small pixels that correspond to the average pixel as follows:

$$\text{gain_1} = (\text{upper left corner small pixel (source)} - \text{average pixel (source)}) / (\text{upper left corner small pixel (principal Auxiliary} - \text{average pixel (princ. aux.)}))$$

Similarly gain_2, gain_3, and gain_4 are calculated for the other 3 corners. The four conditional gains can be combined into one gain relating the average source pixel to the average pixel of the principal auxiliary image for each color of the source image. The one gain may be determined by any convenient method, including taking the median or the average of the four conditional gains, with a provision for handling infinite gains resulting from zero denominators. For example, unless all four small-pixel conditional gains are infinite, the infinite ones may simply be ignored when finding the median or mean of the remaining ones. If all four are infinite, the average pixel gain may be set arbitrarily to zero or the pixel may be ignored for codebook formation purposes.

After calculating gains for each average pixel and each color of the source image as described above, each average pixel can now be represented as a four-dimensional intensity vector and a three dimensional gain vector. The four-dimensional intensity vector includes four values corresponding to the intensity of the red, green, blue, and panchromatic bands of each average pixel determined in step 104. In general, the intensity vectors represent the imaged characteristics of objects or materials appearing in a sensor field of view and may be expected to be substantially uniform for each type of object or material. The three-dimensional gain vector includes three gains relating differential changes in the principal auxiliary image panchromatic pixel to differential changes in each color of the source image calculated as explained above.

Since there are typically a large number of average pixels in an image, some form of clustering is required to represent the characteristics of the imaged materials present in the images in a reduced set of intensity vectors. A simple method of vector quantization is the following: Take the first four-dimensional intensity vector as a cluster center and store it in the first position of the codebook. At each position in the codebook also store, for example, the gain vector and the number of pixels (np) represented by this cluster center. For every other pixel, compare its four-dimensional intensity vector with every stored intensity vector in the codebook. If it is close to one of the stored intensity vectors, average its gain vector with the gain vector of the stored vector weighing the previously stored gain vector by np, and incrementing np by 1. If it is not close, store the intensity vector and its associated gain vector as a new entry in the

codebook. To determine whether or not the intensity vectors are close, a distance measure needs to be selected and a threshold set. Typical distance measures are Euclidean, sum of absolute differences of the components of the intensity vector, and maximum of the absolute differences of the components of the intensity vector.

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After the codebook is filed in this manner, there will typically be many cluster centers for which the associated np is small. These usually represent noise pixels. Therefore, all entries for which np is less than some second threshold should be eliminated.

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Rendering of the higher-resolution source image is accomplished as follows: Define "large pixel" as the smallest pixel of the original source image and a pixel of the same size in the principal auxiliary image, which typically must be calculated by averaging smaller pixels present in the principal auxiliary image. Define "small pixel" as the desired pixel size of the enhanced source image.

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Typically, there are four small pixels covering the same area as one large pixel, but different mappings are possible. The only requirements are that the small pixels of the principal auxiliary image match the small pixels of the enhanced source and that an integral number of small pixels are covered by one large pixel.

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In step 114, each large pixel of the source image 34 is subdivided into small pixels (typically a 2x2 array). In step 116, for each small pixel of the corresponding large pixel of the principal auxiliary image, compute the difference between it and the large pixel intensity (which is the average of all of the small pixels it covers). Then, in step 118, for each small pixel, retrieve from the an

codebook entry having a four dimensional intensity vector to which the corresponding large pixel's 4 dimensional intensity vector is the closest. In step 120, the processor computes the small pixel intensity of the enhanced source image as the intensity of the large source pixel + (the associated gain) times (the difference between the small pixel and large pixel of the principal auxiliary image) for each color.

5 B. Other Clustering Techniques

Many other clustering techniques besides vector quantization are known in the literature. Any of these can be used to find prototypes with associated gain. 10 However obtained, these prototypes can be used for rendering a final image in the same way.

15 C. K Nearest Neighbor (KNN)

Assuming that the clustering was accomplished as in A or B above, the associated gain vector used in rendering each small pixel of the enhanced source 15 image could be the average of the K most-similar codebook entries.

20 D. General Regression Neural Network (GRNN)

Assuming that the clustering was accomplished as in A or B above, the associated gain used in rendering each small pixel could be determined using a GRNN neural network wherein the center of each node is a cluster center of the codebook, and each node is weighted by its associated np value. In this case, the gain used for rendering is a weighted average of all the associated gains in the 20 codebook. The weighting for each gain is the associated np times exp (-

distance²/sigma²). Alternatively, the weighting for each gain could be the associated np times exp (the distance/sigma).

E. Probabilistic Neural Network (PNN)

Assuming that the clustering was accomplished as in A or B above, the
5 associated gain vector used in rendering each small pixel could be determined
using a PNN neural network wherein the center of each node is a cluster center of
the codebook, and each node is weighted by its associated np value. In rendering,
the category would be determined by PNN classification of the auxiliary vector (4
dimensional intensity vector in the example) and the gain vector used would be
10 the center of the range used to define the category.

F. Multi-Layer Perceptron (MLP)

In this case clustering is not necessary as a preprocessing step, but could
be used. Input to the MLP would be a series of vectors representing each large
pixel. Each vector would be, as in A, composed of the intensity values of that
15 pixel for each of the co-registered image planes available, with an associated
target gain as computed in A. In rendering each small pixel, the large pixel
intensity vector is input to the MLP. Its output is the gain vector which should be
applied to the small pixel differences.

G. Other regression techniques

20 The MLP forms a non-linear regression of gain relative to the input vector.
Any other regression technique could be used in the same way. Suitable
techniques include the Group Method of Data Handling (GMDH), and radial basis
function estimation (RBF).

While simple conditions were assumed above for illustrative purposes, each neural network may be significantly more complex than described above and may include more inputs than described above.

After all of the pixels 82 of the source image 36 have been mapped to new
5 values based on the pixel differences of the auxiliary image and the gain values,
the new pixels 82 are output in step 120 as the processed image. The processed,
source image has a higher resolution than the original source image.

Although specific embodiments of the present invention have been
described, it will be understood by those having ordinary skill in the art that
10 changes may be made to those embodiments without departing from the spirit and
scope of the invention.

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CLAIMS:

What is claimed is:

1. A method of increasing the sharpness of a source image based on at least one auxiliary, co-registered image(s) of a higher degree of sharpness, wherein the source and auxiliary images comprise a plurality of pixels with corresponding spectral intensities, and wherein the spectral intensities of co-located pixels in the source and one or more auxiliary images define an intensity vector for each co-located pixel, comprising:
 - 5 resampling the source and the auxiliary image to a common, lower resolution;
 - 10 determining for each source image pixel a gain relating a differential change in intensity in the source image pixel with a differential change in intensity of a corresponding auxiliary image pixel, based on the common, lower resolution;
 - 15 deriving a mapping function correlating determined gains with corresponding intensity vectors;
 - 20 subdividing each pixel of the original source image into a plurality of small pixels, each small pixel of the original source image corresponding in size and location to a small pixel in the auxiliary image; and modifying the intensity of each subdivided source pixel based on differences in intensities between the small and large pixels in the auxiliary image and an interpolated gain from the mapping function.

2. The method of claim 1, wherein each of the large source pixels is subdivided into $N \times M$ pixels in the subdividing step.

3. The method according to claim 2, wherein N is equal to M .

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4. The method according to claim 2, wherein N is not equal to M .

5. The method according to claim 1, wherein the intensity vector includes at least two spectral intensities for each pixel.

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6. The method according to claim 1, wherein the deriving step includes creating a codebook relating intensity vectors to at least one corresponding gain value based on the determining step.

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7. The method according to claim 6, wherein the creating is performed according to vector quantization.

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8. The method according to claim 6, wherein the modifying is performed according to a weighted average of the gain value for each intensity vector in the codebook.

9. The method according to claim 6, wherein the modifying is performed using a general regression neural network having node centers based on the intensity vectors in the codebook.
- 5 10. The method according to claim 6, wherein the modifying is performed using a probabilistic neural network having node centers based on the intensity vectors in the codebook.
11. The method according to claim 1, wherein the determining, deriving,
10 subdividing and modifying steps are performed based on a plurality of co-located auxiliary images.
- 15

ABSTRACT

A method increases the spatial resolution of a source image based on an auxiliary, co-registered image of a higher spatial resolution. Each of the source and auxiliary images includes a plurality of pixels with corresponding spectral intensities and the method includes reducing, identifying, deriving, subdividing and modifying steps. Multiple auxiliary images can be used with the method.

In the reducing step, a spatial resolution of the auxiliary image is reduced to a common resolution with the source image. Then in the identifying step, corresponding groups of pixels at the common resolution in the source and auxiliary images are identified. Then in the deriving step, a mapping function is derived which relates the rate of change of intensity of each group in the auxiliary image and the corresponding rate of change of intensity in the corresponding group in the source image to the intensity vector. This map can be conditioned on any number of auxiliary image planes.

In the subdividing step, each source pixel is subdivided. Then in the modifying step, the spectral intensity of each subdivided source pixel is modifying based on the map and the local intensity variations of the auxiliary image. This results in increasing the resolution of the source image.

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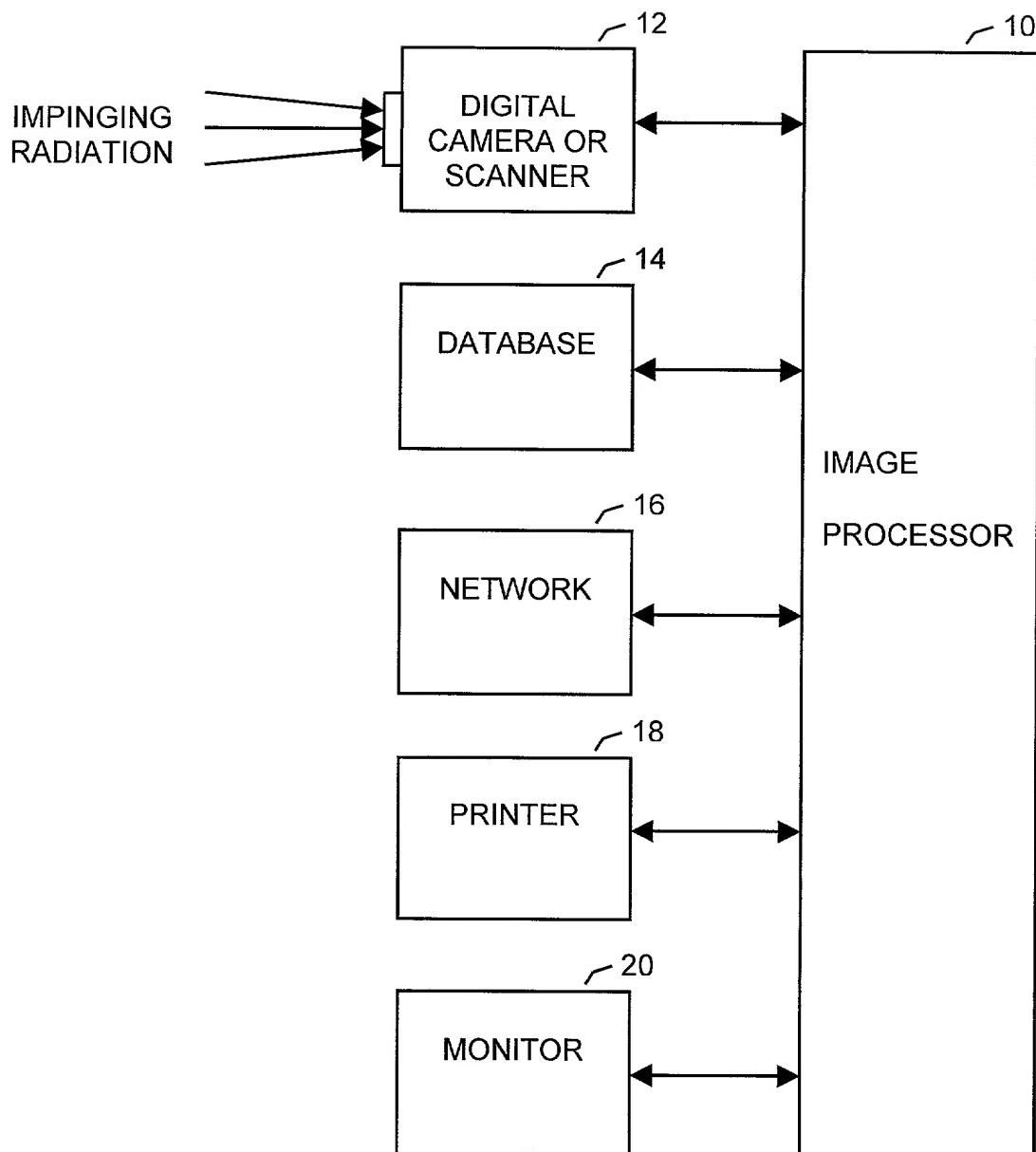
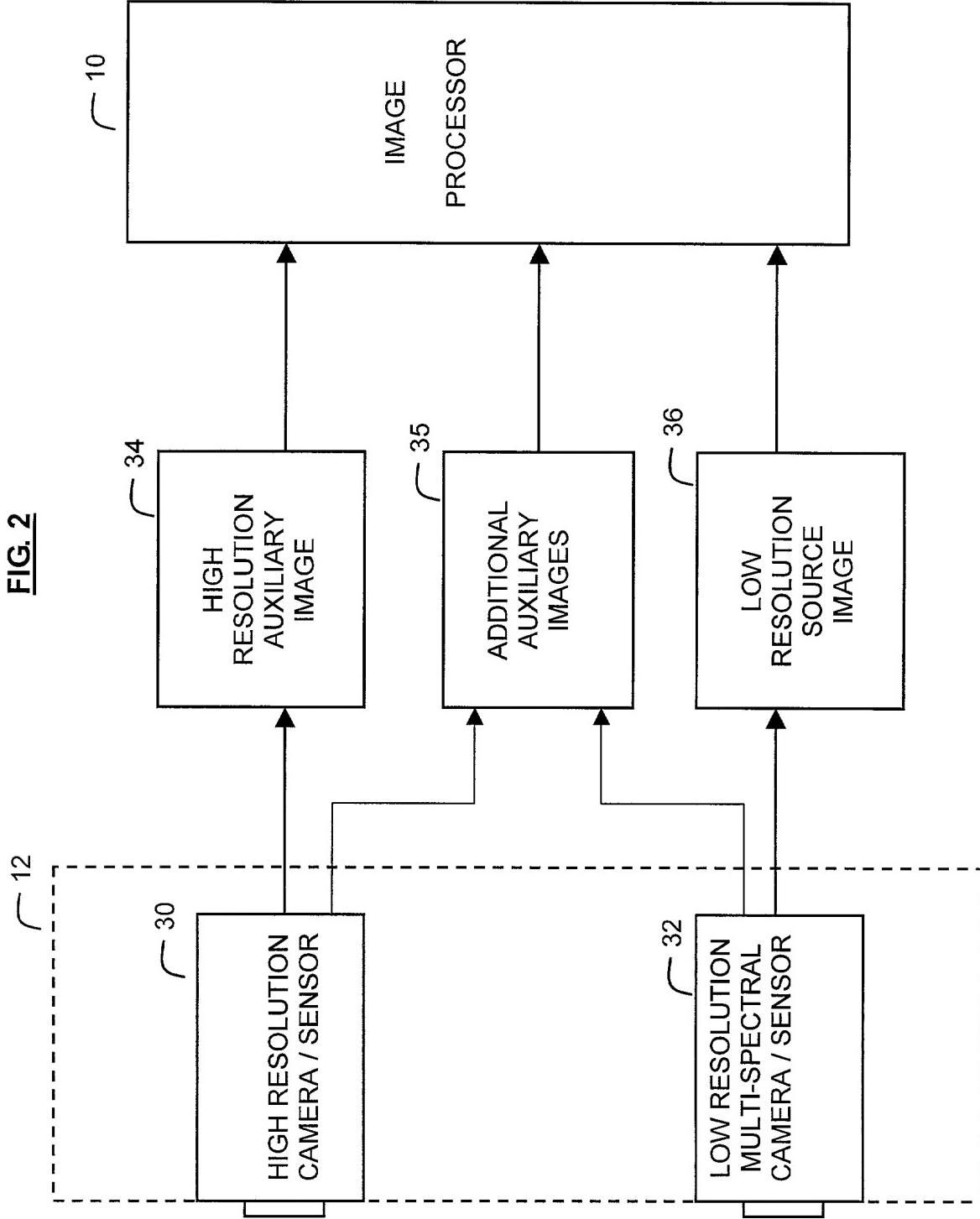


FIG. 1

FIG. 2



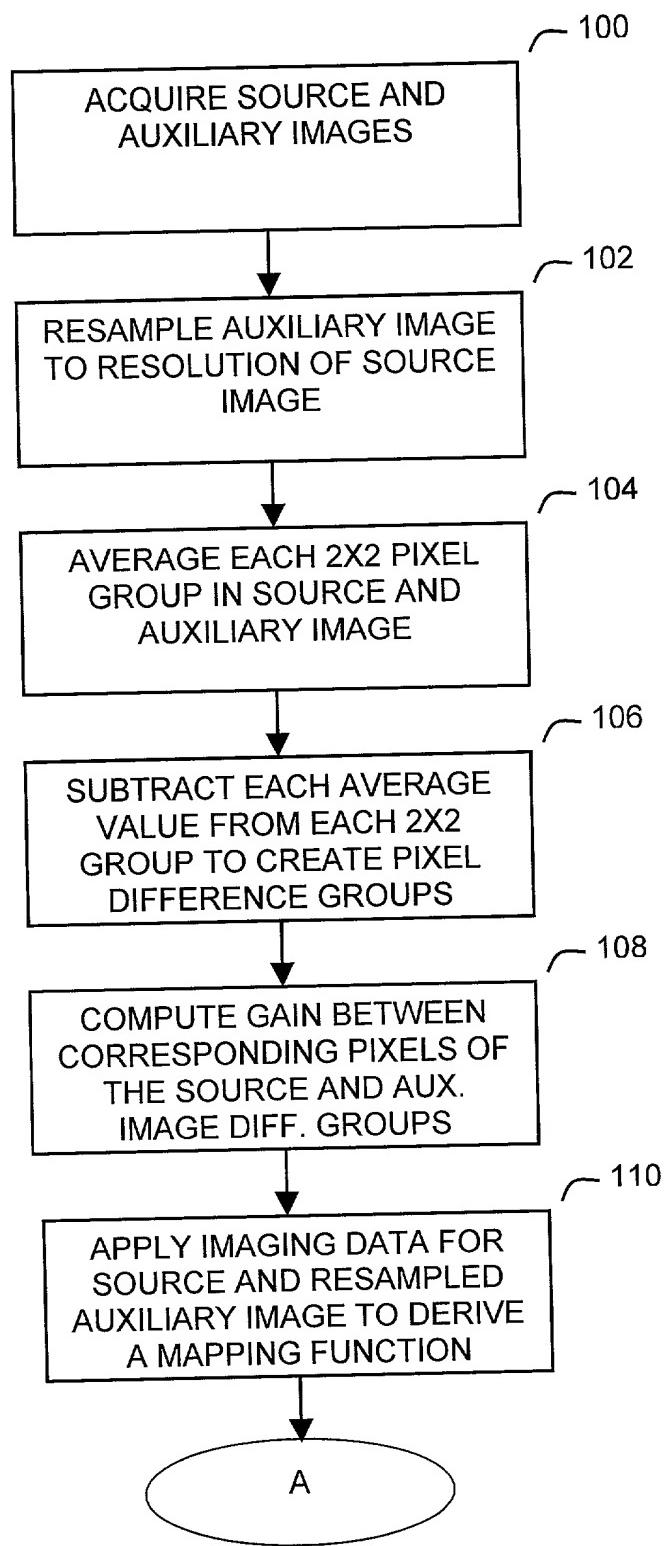


FIG. 3A

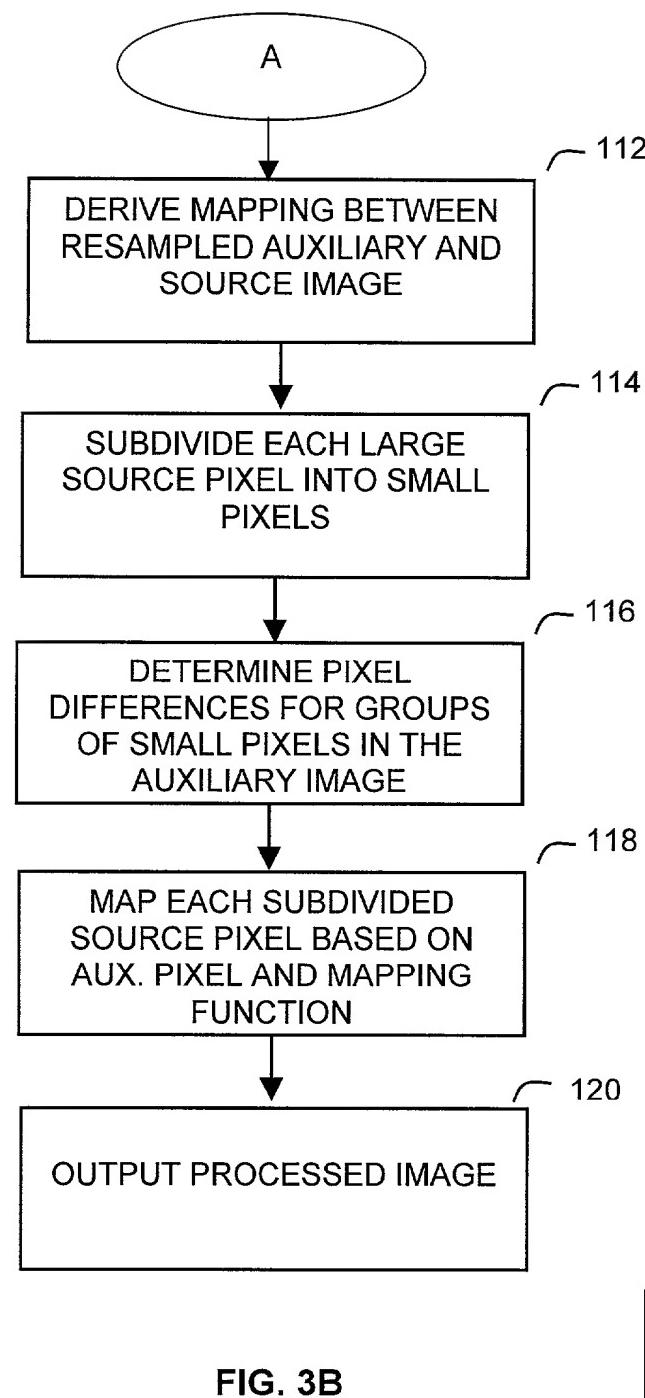


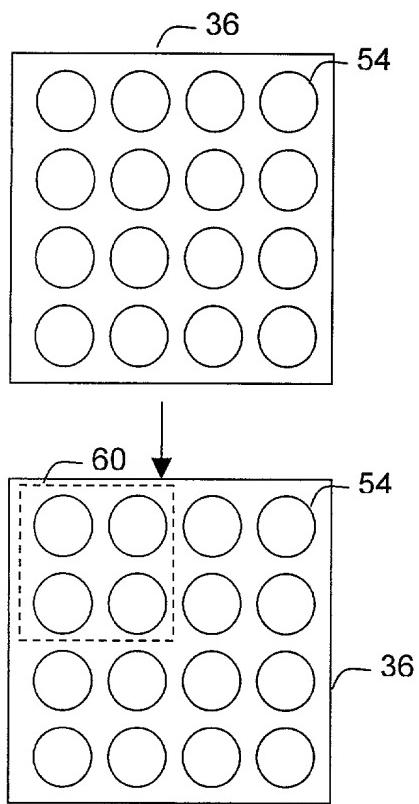
FIG. 3B

FIG. 3A

FIG. 3B

FIG. 3C

SOURCE IMAGE



AUXILIARY IMAGE

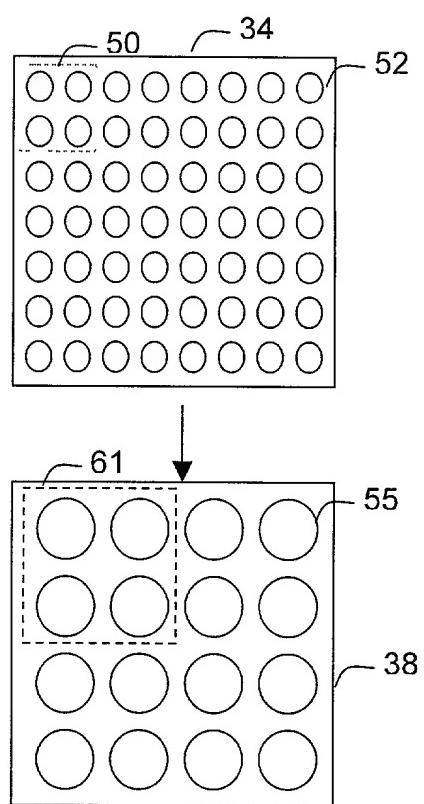


FIG. 4

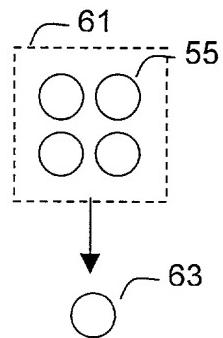
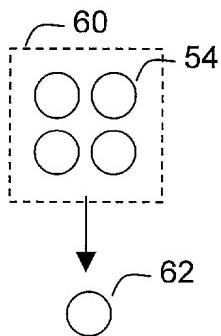


FIG. 5

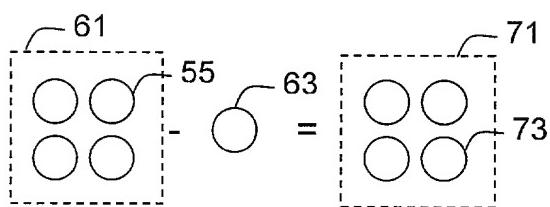
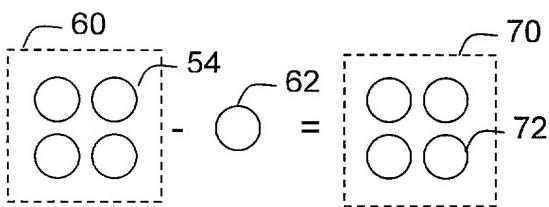


FIG. 6

SOURCE IMAGE

AUXILIARY IMAGE

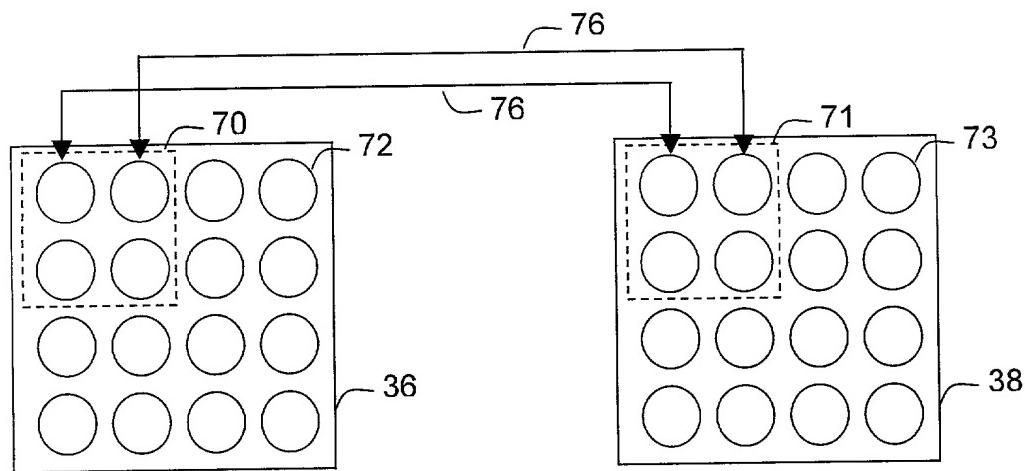


FIG. 7

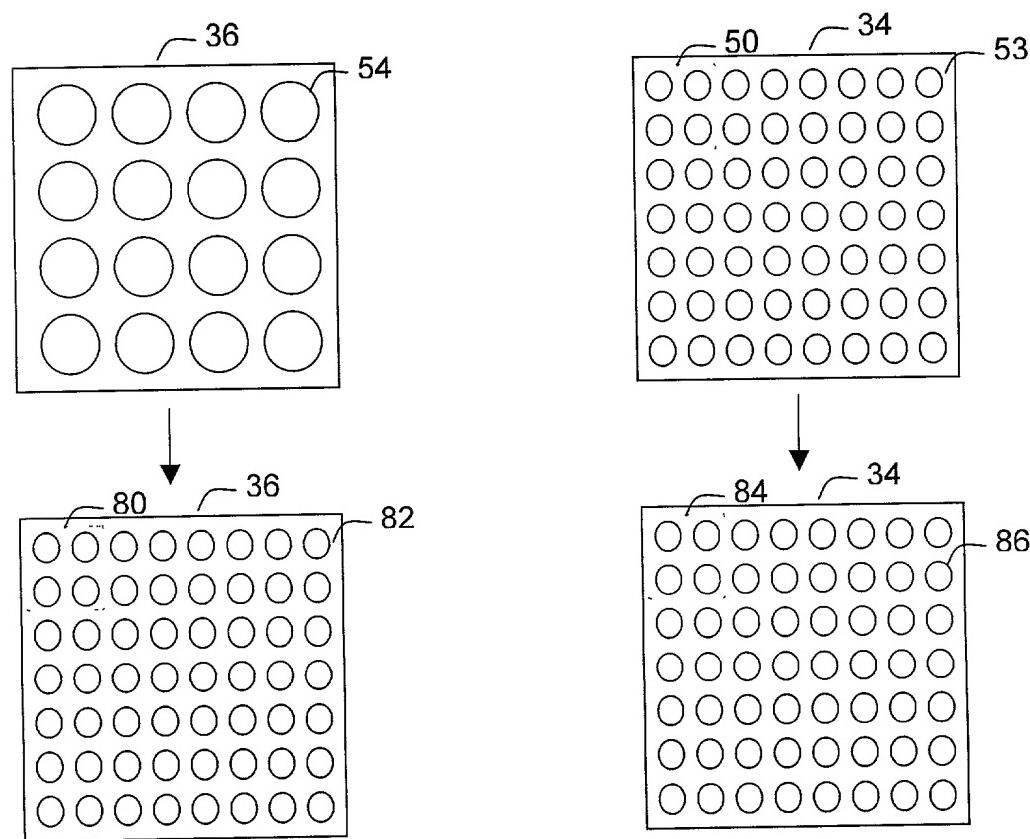


FIG. 8

SOURCE IMAGE

AUXILIARY IMAGE

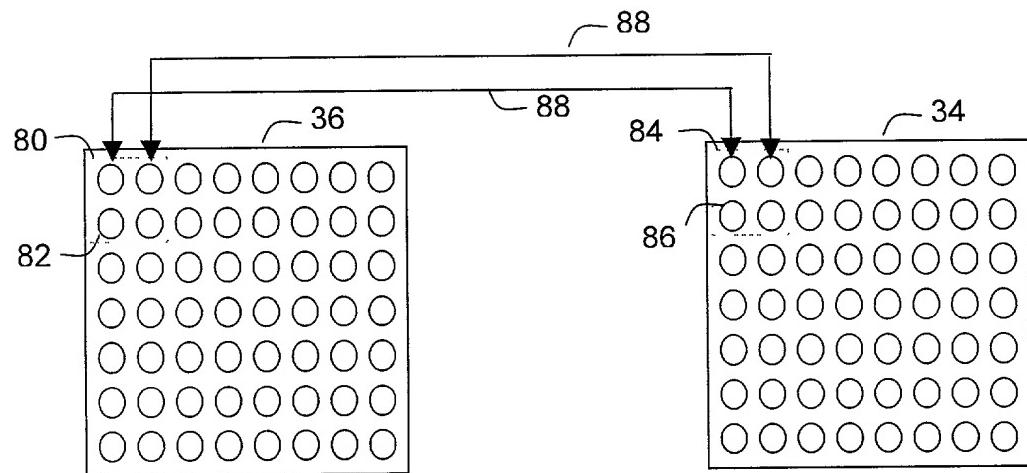


FIG. 9

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